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Observations and Computations of Higher Energy Collective Effects in the Fermilab Booster

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Observations and Computations of Higher Energy Collective Effects in the Fermilab Booster*

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1. Introduction

This report analyzes the results of experiments I have participated in during my visit to Fermilab in November and December 1986. The aim of the experiments was to shed some light on the observed horizontal beam size growth in the Booster.

A computational study of the effect of the impedance of the radio-frequency accelerating cavities has been carried out, and the results are compared with the experimental observations.

Finally, possible cures for the instabilities are discussed.

2. Beam size and bunch length measurements.

2.1 Experimental results. Experiment of the 10/12/86, experimentalists Max Cornacchia and Jim Crisp (p. 93 of Booster Log 5).

The horizontal beam size was measured with a flying wire. At the same time, the bunch length was also measured with the longitudinal pick-up. Since we suspected that the parasitic modes in the rf cavities are responsible for the observed increase in beam size, we carried out the measurements with 4 out of the 18 cavities either turned off or shorted. The circulating beam intensity at high energy was 1.5×10^{12} protons (3 turns injection). No losses were observed after transition (19 msec after injection). The injected beam intensity was 3×10^{12} protons.

Fig. 1 shows a plot of the measured beam half size (assumed here to be 2 times the rms value calculated from the flying wire data). Apologies are being offered for not including error bars in the plot. Repeated measurements indicate good reproducibility--with error bars less than 0.5 mm--in absence of large anomalous increase in beam size. When an instability is present, as evidenced by beam blow up, the measurements of beam size are much less reproducible. The lattice parameters at the observation point are: $\beta_x = 6.5$ m, $X_p = 1.8$ m.

Fig. 1 indicates an increase in beam size at transition (19 msec after injection), independent of shorting or not shorting the cavities, which is to be expected. We also observe that the horizontal beam size increases at high energy, and that the increase is more pronounced when 4 cavities are not shorted.

The measured beam size with cavities not shorted is compared with the calculated value, obtained by adding quadratically the contribution of the momentum spread and the horizontal emittance. The momentum spread was inferred from the measured bunch length and the known rf parameters. For the betatron beam size, we have assumed a constant normalized emittance of 8π mm-mrad. The good agreement between the two curves indicates that, at this intensity, no betatron blow up occurs, and that the longitudinal instability only is responsible for the observed increase of beam size.

In Fig. 2 the measured beam size with cavities shorted is compared with the ideal situation of constant longitudinal bunch area (equal to

0.025 eV-sec) and transverse normalized horizontal emittance (equal to 8 π mm-mrad). Apart from the initial point right after injection (where the measurements are not very reliable) there is good agreement up to 28 milliseconds, where the anomalous beam size increase starts to occur.

In Fig. 3, the bunch area, calculated from the measured beam size, is plotted as a function of the time in the cycle, with shorted and unshorted cavities.

2.2 Experimental results. Experiment of the 12/8/86, experimentalists Max Cornacchia and Jim Crisp (p.67 of Booster Log 5).

Beam size and bunch length measurements were also made at a higher injected beam intensity. Five turns injection was used, giving 3×10^{12} injected protons into the Booster, of which 2.2×10^{12} survived past transition. Fig. 4 shows the measured and predicted beam sizes at various times in the cycle. The measured beam size is denoted by the legend "sextupoles on, measured", to differentiate it from similar measurements in which the horizontally correcting chromaticity sextupoles were turned off. Fig. 4 shows that, as in the experiment described in the previous section, the trend of beam size in the cycle agrees closely with the value given by the measured bunch length and a constant transverse normalized emittance equal to 8 π mm-mrad. The latter is denoted in the legend as "Et=8π, measured bunch area A".

The theoretical beam size predicted under the assumptions of constant normalized emittance (8π mm-mrad) and bunch area (0.03 eV-sec), and denoted by the legend "Et = 8π, A = 0.03" in Fig. 4, shows a discrepancy from the measured value at around 25 msec, indicating the beginning of a longitudinal anomalous increase at this time. The three curves show a different behaviour early in the cycle; close to injection energy, however, the measurements are less reproducible and the beam size pattern less smooth.

This second set of measurements, performed at higher beam intensity, confirms the results discussed in the previous section. The anomalous increase in beam size at high energy seems to be related to a longitudinal instability. Based on the present investigation, we have found no evidence so far of a horizontal emittance increase, driven by transverse collective effects at high energy. This conclusion has to be reconciled with the results obtained when the horizontal chromaticity sextupoles were turned off (p. 67 of Booster Log Book 5). It was found that the sextupoles have the effect of reducing the size of the extracted beam. This is shown in Fig. 5, where the measured beam sizes are plotted with and without the horizontal chromaticity sextupoles. It can be seen that the correction of the chromaticity has some influence on the beam size at high energy. It is possible that switching the chromaticity sextupoles off triggers a transverse instability. However, the theoretical predictions (discussed in the next paragraph) indicate that, at high energy, the beam intensity should be well below the threshold for the transverse collective instabilities, regardless of the value of the chromaticity. Thus, the effect of the chromaticity sextupoles is not understood. It is also possible that the observed effect is a single particle phenomenon related to the tune spread in the beam and the crossing of resonances, rather than to a transverse collective instability. The coincidence of the sextupole effect with the increased momentum spread caused by the longitudinal instability, which occurs at about the same time, encourages this interpretation. More experimental work is needed to confirm this hypothesis.

3. Theoretical prediction

3.1 Longitudinal coupled bunch instabilities.

We have computed the growth times and thresholds of the longitudinal coupled bunch oscillations. The driving terms of the instability were assumed to be the accelerating rf cavities. Measurements of the longitudinal cavity modes were provided (Ref. 1). Table 1 lists the frequencies, shunt impedances (for the total 18 cavities) and Q's.

TABLE 1

Measured resonant frequency, shunt impedance and Q of the Booster accelerating cavities.

Frequency (MHz)	Shunt Impedance (Mohm)	Q
52.3	0.43	1300
85.8	1.56	3380
109.7	0.15	2258
167.2	0.07	1960
171.5	0.07	1190
225.4	0.33	2090
318.1	0.09	1570
342.6	0.50	530
391.0	0.11	460
448.8	0.48	3590
559.7	0.07	430
685.9	0.71	2440

The above values were measured with a fully biased ferrite current. Thus, they do not reflect the situation occurring at low energy. For the present study we have made the approximation that the characteristics of the parasitic modes do not change with energy. (The frequency change is small past 16 msec after injection.) The computations of the instability were performed with the code ZAP (Ref. 2).

In Fig. 6 we have plotted the growth times of the first four coupled bunch modes (dipole, quadrupole, sextupole, octupole) at various times after injection. The longitudinal beam characteristics (bunch length, momentum spread and beam intensity) are experimentally measured and described in Section 2.1. The growth times of the fastest instabilities are of the order of a millisecond or less. The stable situation at 32 milliseconds after injection is a consequence of the large increase in bunch area. The simulation indicates that the bunch area increases until stability is reached.

In Fig. 7, the growth times of the fastest mode are plotted as a function of the bunch area at the (total) beam energy of 8.7 GeV, 32 msec after injection. The observed bunch area blow up (Fig. 3) is qualitatively consistent with a growth time that is considerably longer than the time before the beam is extracted (approximately 2 msec).

Finally, Figs. 8 and 9 show the growth times and coherent synchrotron frequency shifts which occur if a constant bunch area (equal to 0.018 eV-sec) and a beam intensity of 2.5×10^{12} protons is assumed at peak energy. The growth times of the instability are fast, much shorter than a msec. These results provide an useful indication for the specifications of feedback systems and the synchrotron frequency spread required to damp the instabilities.

The beam current threshold for the single bunch longitudinal microwave instability driven by the parasitic modes in the rf cavities has also been computed and found to be, in the worst case, of the order of 2.8×10^{11} protons per bunch, much higher than the maximum circulating beam current in the Booster. It must be noted, however, that no information is available (at least to us) on the broad-band impedance of the ring caused by other distributed cavity-like objects, which should be added to the contribution of the rf cavities.

3.2 Transverse instabilities

No information is available on the transverse deflecting modes of the Booster cavities. The computer code URMEL has been used to compute these modes (Ref. 3). Table 2 contains a list of the resonant frequencies predicted by URMEL.

TABLE 2

Resonant frequencies, transverse impedances and Q's as computed by URMEL for the Booster cavities. The transverse impedance refers to the total 18 cavities in the ring.

Frequency (MHz)	Transverse Impedance (Mohm/m)	Q
694.1	3.8	26200
744.8	2.4	27780
797.8	5.0	27790
1083.2	38.7	32550
1137.4	1.3	33420
1199.5	3.7	35390
1239.2	1.7	36820
1266.1	11.5	35610
1286.0	1.9	33860
1438.6	4.1	44610

The result of the ZAP study is that the rise times of the transverse coupled bunch oscillations are much longer than the acceleration time, with the sole exception of a short time interval around transition energy, where a growth time of 6 msec is predicted at the intensity of 2.5×10^{12} protons for the rigid dipole mode when the chromaticity is not corrected. A zero chromaticity raises the growth time to 10 msec. For the higher order modes, the rise times are of the same order or longer than the acceleration time, regardless of whether the chromaticity has been corrected or not.

The growth times of the single bunch instabilities (head tail modes) have also been computed, and found to be much longer (tens of milliseconds) than the acceleration time at all energies. Finally, the transverse microwave instability has a current threshold even higher than the longitudinal one discussed earlier on, and is far above the maximum circulating current in the Booster.

4. Conclusions from experimental results and computations of instability growth times.

a) Strong coupled bunch longitudinal instabilities are driven by the rf cavities. These instabilities are particularly strong a few milli-seconds before the beam is extracted from the Booster and are responsible for all (or most) of the observed increase in beam size. The growth times are fast compared to the acceleration time (of the order of a millisecond or shorter).

b) Based on the results of the experiments discussed in this report, there is no evidence of transverse coupled bunch oscillations. The measurements of beam size are in qualitative agreement with the calculations derived from the assumptions of a constant normalized emittance, equal to 8π mm-mrad. The predictions of the growth times of the transverse coupled bunch oscillations indicate that these are long and should not cause any emittance increase. For a short time around transition, however, some emittance blow-up is possible.

c) The horizontal chromaticity sextupoles have little effect on the beam size, except at high energy, in correspondence to the blow up of the longitudinal emittance. The effect is perhaps due to an increase in tune spread.

5. Possible remedies against longitudinal coupled bunch instabilities.

In this section we briefly discuss ways to stabilize the beam against longitudinal oscillations.

5.1 Lowering the impedance of the parasitic accelerating cavity modes.

We have simulated the damping of the cavities by proportionally decreasing both the shunt impedance and the Q of the accelerating cavities by the same factor. We have studied the effectiveness of this method by computing the growth times of the instability as a function of this reduction factor. The fundamental accelerating mode was not changed. The beam energy (total) in the simulation was 8.8 Gev (about 32 milliseconds after injection); the bunch area 0.018 eV-sec and the circulating beam current $2.5\text{X}10^{12}$ protons. The results of the study are shown in Fig. 10, where the growth times of the first three coupled bunch modes are plotted as a function of the shunt impedance reduction factor. A reduction of the cavity impedances for the parasitic modes by at least a factor 30 is required in order to obtain rise times that are sufficiently long compared to the time left before the beam is extracted.

5.2 Feedback system

The dipole modes of oscillations can be damped with a feedback system of bandwidth of the order of 25 MHz, and acting on individual bunches. The maximum voltage per turn required by the system is given by

$$V = \frac{2E\varepsilon}{\tau f_{rev}}$$

where ε is the relative momentum error acted on by the feedback system, E is the beam energy, f_{rev} the revolution frequency, τ the rise time of the instability. The latter has been computed under various conditions. Fig 8 gives the worst case of a bunch area of 0.018 eV-sec at peak energy and a circulating current of 2.2×10^{12} protons. Under these conditions, a rise time of the order of 0.2 milliseconds is predicted at peak energy. For example, a transverse pick up that detects a position error of 0.2 mm at a location where the dispersion is 1.5 m, gives a minimum detectable relative momentum error of 1.3×10^{-4}. With this value, the minimum voltage per turn required for the feedback system is, at peak energy, 18 kV.

5.3 Higher harmonic cavity

A radio-frequency cavity operating at a multiple of the frequency of the main accelerating cavities allows a control of the synchrotron frequency, the synchrotron frequency spread, and the bunch length. If the higher harmonic system is adjusted so that the slope of the rf wave is zero at the synchrotron phase, a greatly enhanced synchrotron frequency spread results. This increases Landau damping against longitudinal coupled bunch instabilities. The choice of frequency is a compromise between the voltage and the length of the bunch: a higher frequency is more effective in providing large spreads. However, it becomes less effective if the bunch length exceeds the wavelength of the higher harmonic oscillation. For the Booster, we have considered a fourth harmonic cavity. In order to maximize the synchrotron frequency spread, the first and second derivative of the rf voltage should vanish at the synchronous phase (Ref. 4). Under these conditions, the voltage required by the harmonic cavity is approximately one fourth that of the main rf accelerating voltage. We have computed the synchrotron oscillation frequency as a function of the maximum amplitude of the momentum oscillations. This is shown in Fig. 11, where ν_s is plotted with and without a 4-th harmonic cavity. The following situation was simulated:

Beam energy (total):

8.7 GeV (32 milliseconds after injection)

Main rf accelerating voltage: 446 kV

Synchronous phase of the accelerating voltage: 25 degrees

Ratio harmonic cavity voltage/main rf voltage: 0 or -0.228

Synchronous phase of the higher harmonic cavity: 2 degrees.

The graph indicates the large increase in synchrotron frequency spread obtainable with this cavity. For stability, this spread must be of the same order as the coherent synchrotron frequency shift excited by the instability. The latter has been computed with the code ZAP, and is shown in Fig. 9, in the worst case of a bunch area of 0.018 eV-sec and a circulating beam intensity of 2.2×10^{12}. It can be seen that the shift in the synchrotron tune can be covered with a 4-th harmonic cavity by a momentum spread of the order of 5×10^{-4}. The phase space trajectories with and without a 4-th harmonic cavity are shown in Figs. 12 to 15 for two different initial conditions. There is some bunch lengthening at small amplitudes. No appreciable reduction in bucket area is caused by the 4-th harmonic cavity.

5.5 Synchrotron frequency splitting.

Stabilization against longitudinal oscillations has been obtained by introducing a synchrotron frequency shift between bunches (Ref. 5). This frequency shift can be obtained using an rf cavity operating at a harmonic of the revolution frequency, but not of the main rf accelerating frequency.

6. Summary

We have reported here the results of two experimental studies of beam size and longitudinal parameters in the Booster. The results indicate a substantial growth of the transverse beam size at high energy. This appears to be related to the onset of strong coupled bunch oscillations, of rise time much faster than the cycle time. The computations of the instabilities, carried out with the code ZAP, indicate that the radio-frequency accelerating cavities are mainly responsible. The theory and the experimental evidence suggest that transverse coupled bunch oscillations are not troublesome, except for a short time around transition energy. Possible cure for the instabilities are a bunch-by-bunch feedback system, a higher harmonic cavity or synchrotron frequency splitting. Lowering the shunt impedance of the parasitic modes should achieve, for it to be effective, a shunt impedance reduction of at least a factor of 30.

REFERENCES

1. Jim Crisp, private communication.
2. M.Zisman, S. Chattopadhyay and J. Bisognano, "ZAP user's manual", Lawrence Berkeley Laboratory Report LBL-21720.
3. King Y. Ng has provided the Urmel results on the cavity modes needed for this study.
4. A. Hofmann and S. Myers, "Beam dynamics in a double rf system", CERN ISR-TH-RF/80-26.
5. F. Amman, IEEE Trans. on Nuclear Science, NS-16, 1073-1081 (June 1969).

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Finally, special thanks to Dr. King Ng for having provided me with the results of the transverse modes in the rf cavities, as computed by Urmel.

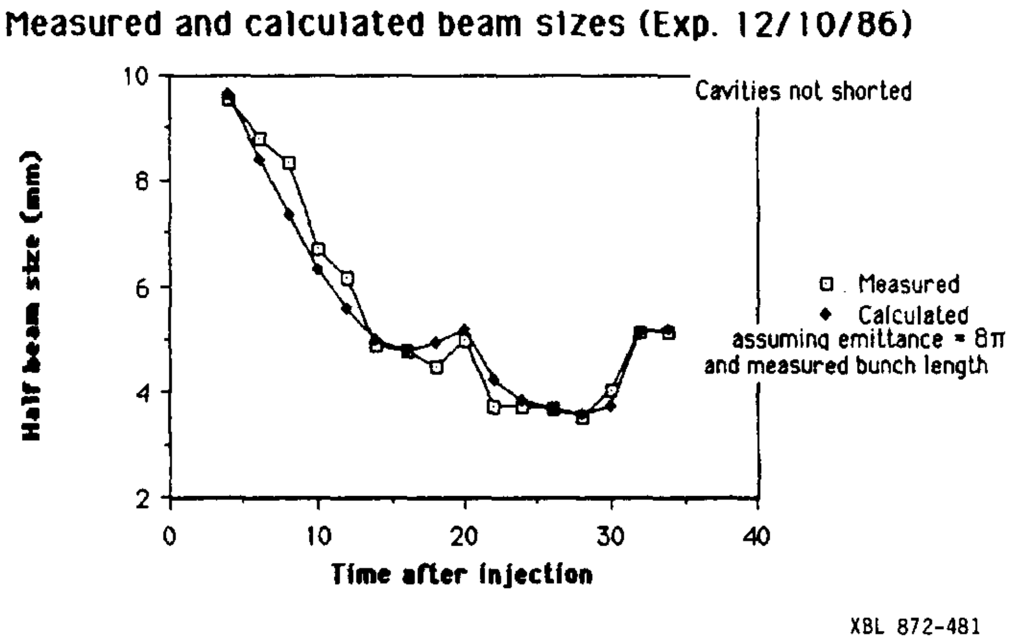

Fig. 1. Measured and calculated beam sizes at various times after injection. Four of the 18 cavities are off, but not shorted.

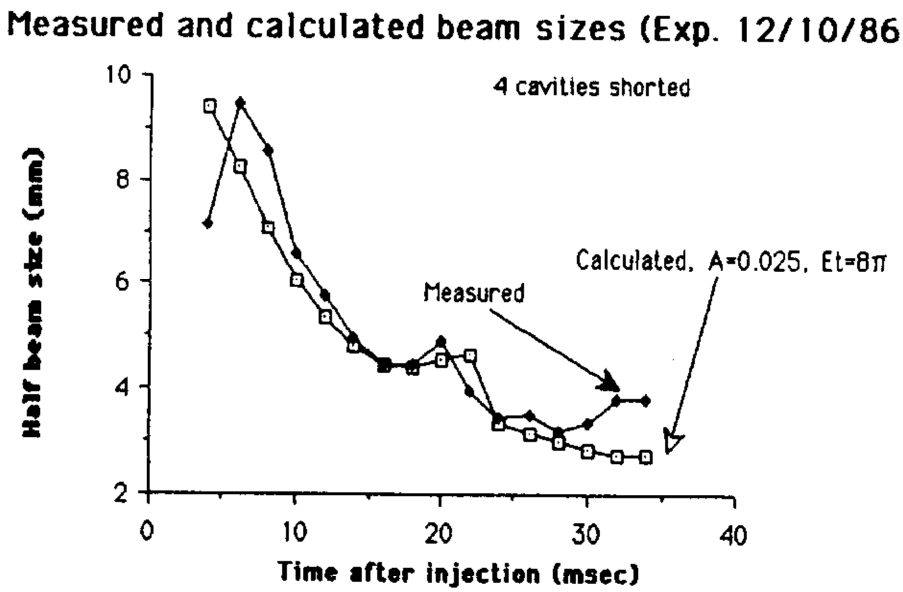

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Fig. 2. Measured and calculated beam sizes with 4 cavities shorted.

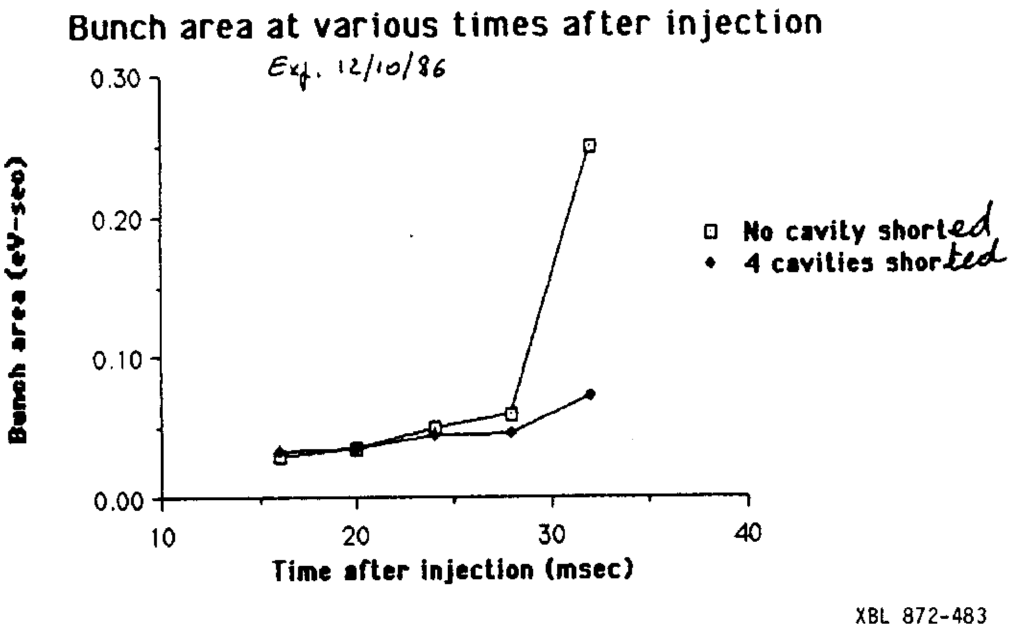

Fig. 3. Bunch area with shorted and unshorted cavities.

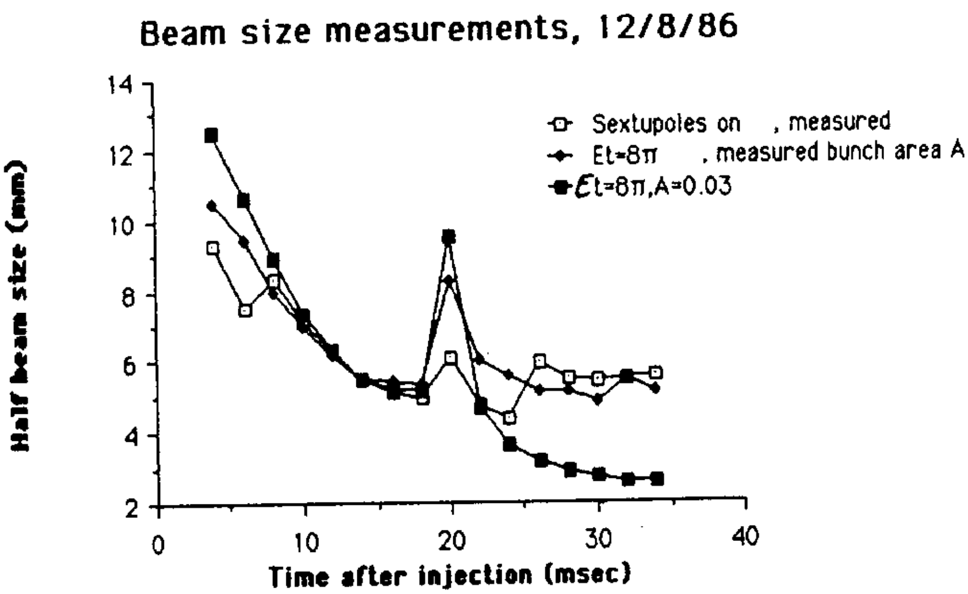

Fig. 4. Measured and calculated beam sizes with five turns injection.

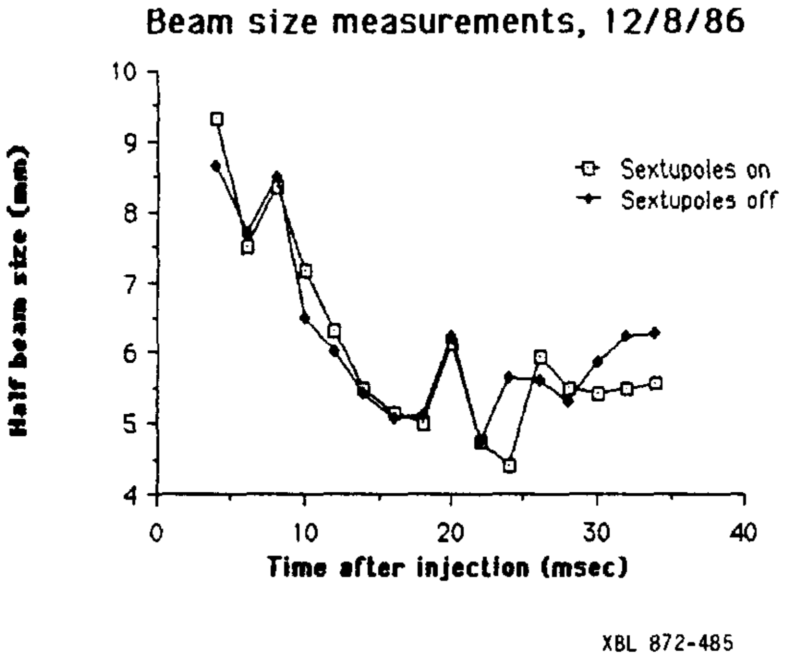

Fig. 5. Beam size with horizontal chromaticity sextupoles on and off.

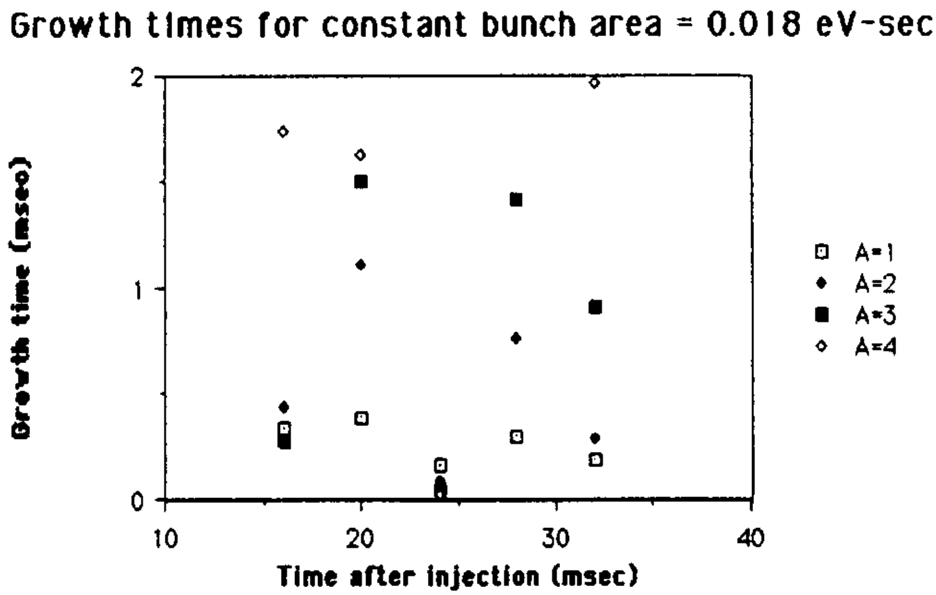

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Fig. 6. Computed growth times of the first four longitudinal coupled bunch modes at various times in the cycles.

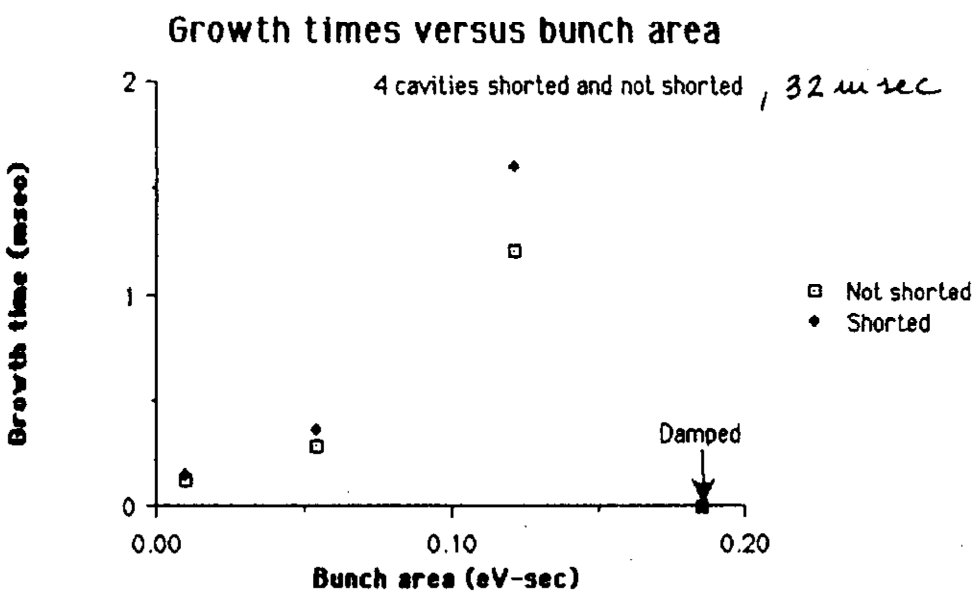

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Fig. 7. Growth times of fastest longitudinal coupled bunch mode versus bunch area at 32 msec after injection with cavities shorted and unshorted.

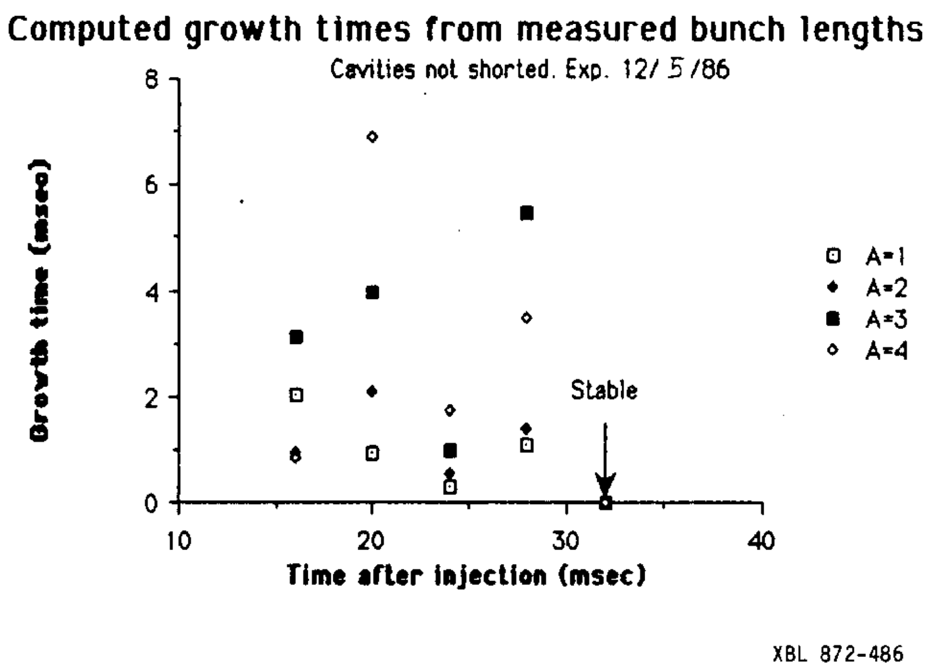

Fig. 8. Growth times of coupled bunch mode A for a constant bunch area of 0.018 eV-sec.

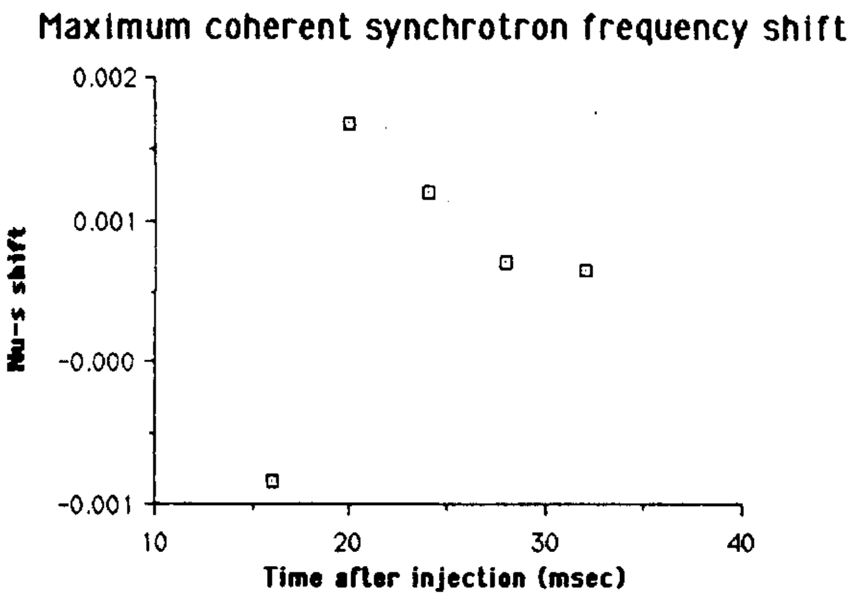

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Fig. 9. Coherent synchrotron frequency shifts under the same conditions as Fig. 8.

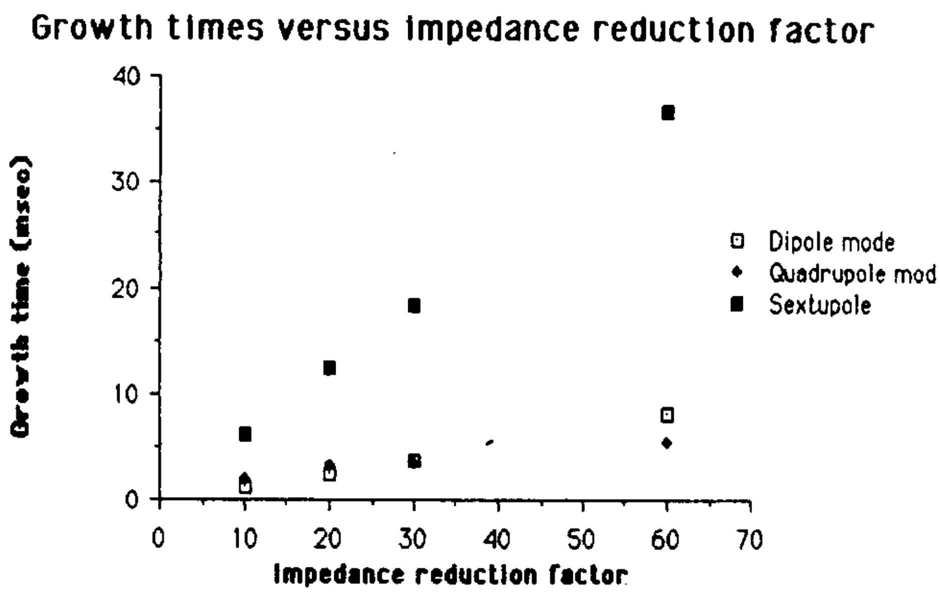

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Fig. 10. Growth times of the longitudinal oscillations at 32 msec after injection as a function of a factor reducing the impedance of the cavities.

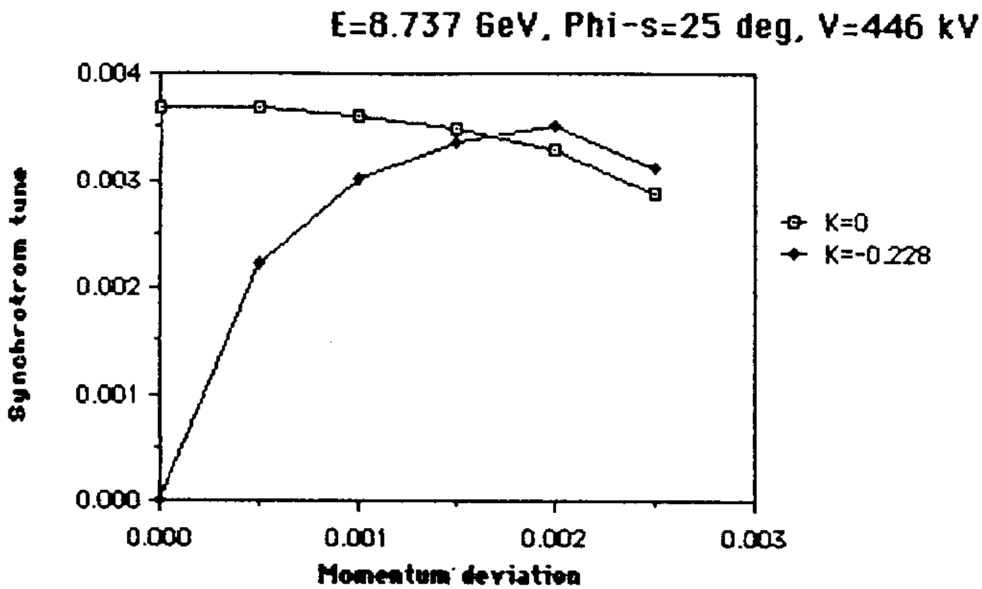

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Fig. 11. Synchrotron tune as a function of the maximum momentum deviation with and without the 4th harmonic cavity.

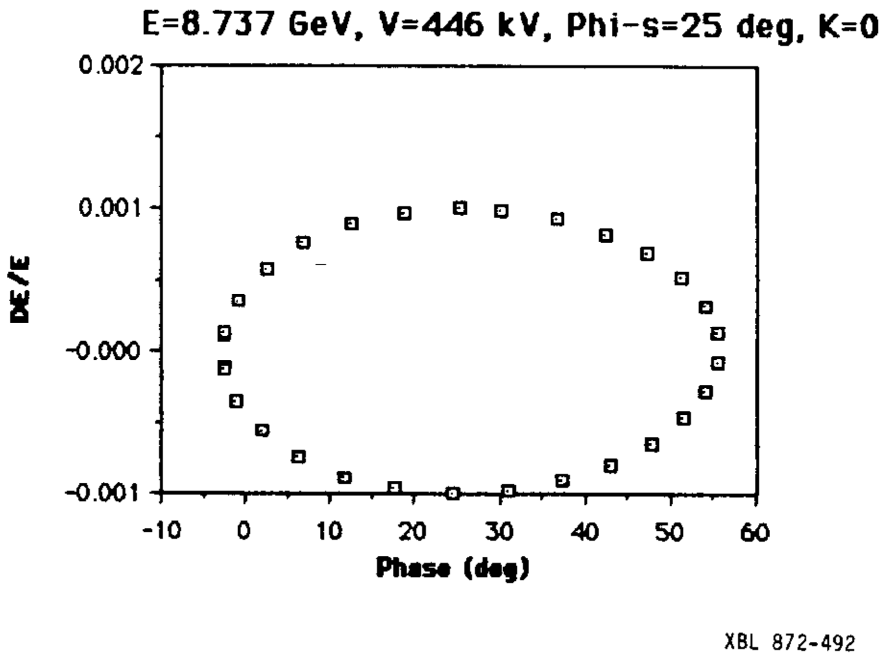

Fig. 12. A phase space plot without 4th harmonic cavity.

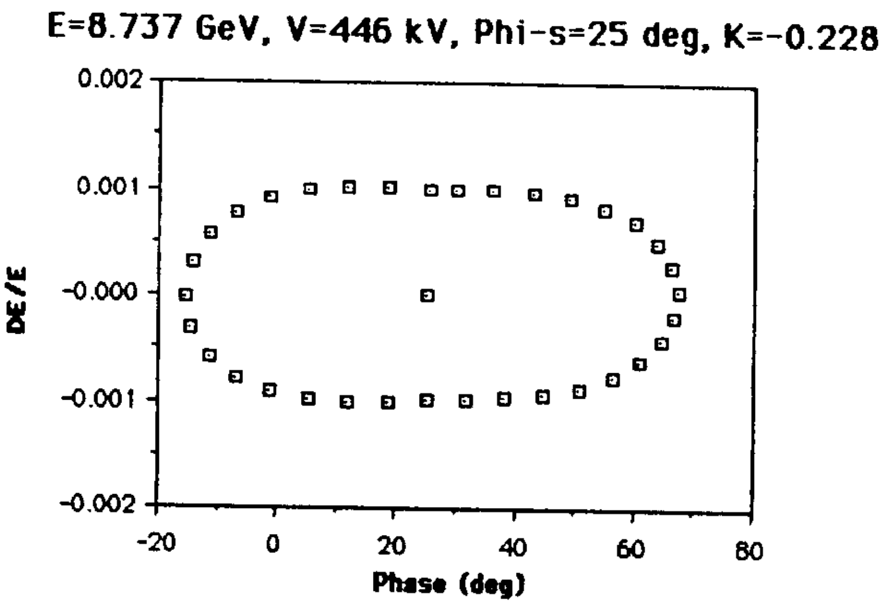

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Fig. 13. Same phase space plot as Fig. 12 with 4th harmonic cavity.

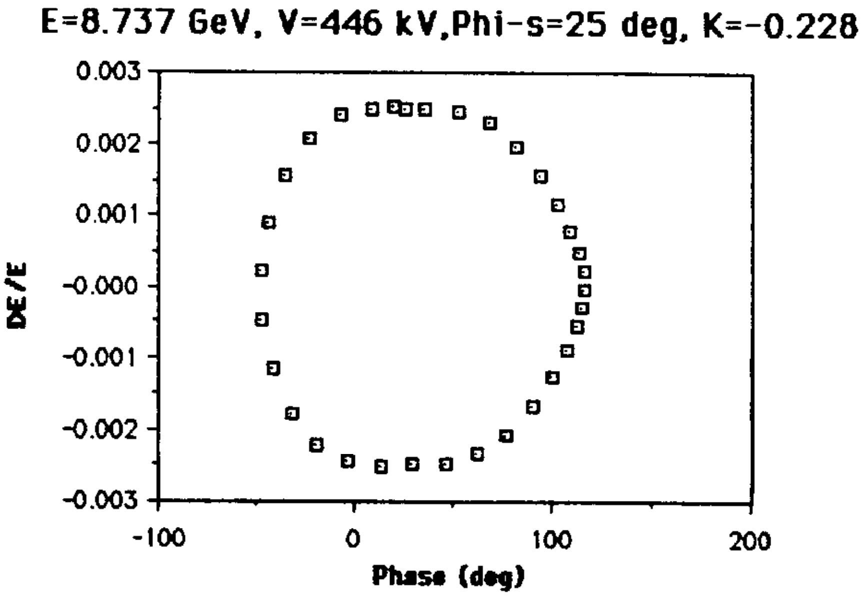

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Fig. 14. A phase space plot without 4th harmonic cavity.

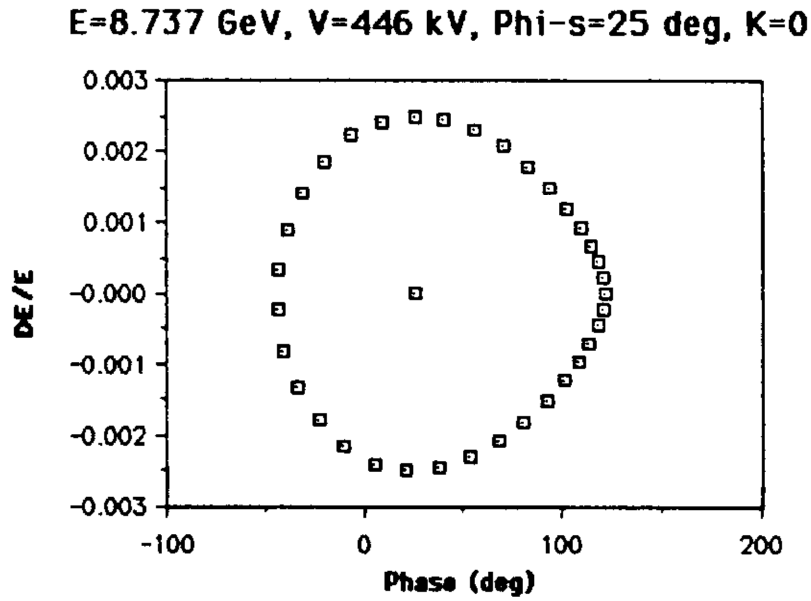

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Fig. 15. Same phase space plot as Fig. 14 with 4th harmonic cavity.